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Carnegie-Mellon University

ACQUISITION OF A MEMORY SKILL

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After more than 230 hours of practice in the laboratory a subject was able to increase his memory span from 7 to 79 digits. His performance on other memory tests with digits equaled that of memory experts with life-long training. With an appropriate mnemonic system, there is seemingly no limit to memory performance with practice.

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One of the most fundamental and stable properties of the human memory system is the limited capacity of short-term memory. This limit places severe constraints on the human's ability to process information and solve problems *(1)*. On the other hand, this limit (about seven unrelated items) stands in apparent contrast to documented feats of memory experts *(2)*. Whether these memory skills are the result of extensive practice or of exceptional ability has often been disputed. The goal of this research is to analyze how a memory skill is acquired.

An undergraduate (SF) with average memory abilities and average intelligence for a college student engaged in the memory span task for about 1 hour a day, 3 to 5 days a week, for more than 1½ years. S.F. was read random digits at the rate of 1 digit per second; he then recalled the sequence. If the sequence was reported correctly, the next sequence was increased by 1 digit; otherwise it was decreased by 1 digit. Immediately after half the trials (randomly selected), S.F. provided verbal reports of his thoughts during the trial. At the end of each session, he also recalled as much of the material from the session as he could. On some days, experiments were substituted for the regular sessions.

During the course of 20 months of practice (more than 230 hours of laboratory testing), S.F.'s digit span steadily improved from 7 to almost 80 digits (Fig. 1). Furthermore, his ability to remember digits after the session also improved. In the beginning, he could recall virtually nothing after an hour's session; after 20 months of practice, he could recall more than 80 percent of the digits presented to him. On one occasion (after 4 months of practice), we tested S.F.'s memory after the session with a recognition test (because recognition is a much more sensitive measure of retention than recall is); he not only recognized perfectly 3- and 4-digit sequences from the same day, but recognized sequences from earlier in the week.

With only a few hundred hours of practice, S.F. would be classified as a beginner at most skills. However, in his field of expertise, memory for random digits, he compares favorably with the best-known mnemonists, such as Luria's S. and Hunt and Love's V.P. *(2)*. For example, after about 6 months of practice, we set S.F. the task of recalling a matrix of 50 digits because data on this task are available for both S. and V.P. S.F.'s study times and recall times were at least as good as those of the lifetime memory experts.

The key to understanding this skill comes from analyses of S.F.'s verbal reports and his

performance on various experimental tests. We will first describe two essential components of this skill: *(i)* his mnemonic associations, and *(ii)* his retrieval structures. Then we will address the question of whether or not S.F. was able to increase his short-term memory capacity.

The most essential part of S.F.'s skill is his mnemonic associations, which he described in great detail in his verbal reports. The principle of a mnemonic is to associate unknown material with something familiar; the advantage is that it relieves the burden on short-term memory because recall can be achieved through a single association with an already- existing code in long-term memory. What S.F. did was to categorize 3- and 4- digit groups as running times for various races *(3)*. For example, 3492 was recoded as "3 minutes and 49 point 2 seconds, near world-record time" *(4)*. During the first 4 months, S.F. gradually constructed an elaborate set of mnemonic associations based initially on running times, and then supplemented with ages (893 was "89 point 3, very old man") and dates (1944 was "near the end of World War II") for those sequences that could be categorized as times. Running times (62 percent) and ages (25 percent) account for almost 90 percent of S.F.'s mnemonic associations.

There are several lines of evidence concerning the mnemonic associations. On the basis of S.F.'s verbal reports, we were able to simulate his mnemonic associations, that is, to abstract a set of rules that categorizes a sequence of digits as 3- and 4-digit running times. When we compared the simulation to the verbal reports, between 85 to 95 percent of the time the computer categorized the digit sequences as S.F. did. By means of the simulation, we were also able to determine which sequences of digits would be categorized as running times and which would not. On the basis of this analysis, we presented S.F. with sequences that could not be associated with running time categories. (This was before S.F. started to use ages to supplement his running times, after about 2 months of practice.) When S.F. was faced with these uncodable sequences, his performance dropped almost to his beginning level. In another experimental session we did the opposite: we presented him with sequences that could all be coded in terms of running times. His performance jumped by 22 percent (from an average of 16 to an average of 19.5 digits).

The mechanism whereby S.F. recodes single digits into 3- and 4-digit units is not sufficient to account for his performance. If S.F. originally had a digit span of 7 digits, and he then learned to recode digits into 4-digit groups, how could he remember the order of more than seven groups of

digits, that is, more than 28 digits? The answer to this question comes from an analysis of his retrieval structures.

Like most people, S.F. initially tried to hold everything in a rehearsal buffer, which stored material in a phonetic code. When he first used his mnemonic associations (session 5), he demonstrated the first rudimentary use of a retrieval structure. He recoded the first 6 digits as two running times, if possible, and he held the last 4 to 6 digits in his rehearsal buffer. He then tried to recall the two running times in order while rehearsing the last few digits. This strategy worked well, and he gradually perfected it over the course of the first 30 sessions until he could recall as many as 18 digits by recoding three groups of 4 digits each as running times and holding the last 6 digits in his rehearsal buffer. At this point, he began to experience real difficulty in keeping the order straight for more than three or four running times (Fig. 1, blocks 8 and 9).

The next important advance came when S.F. introduced organization into his retrieval structure by segmenting his groups into supergroups: he used two 4-digit groups followed by two 3-digit groups and the rehearsal group. From this point, S.F. improved his performance rapidly by increasing the number of groups within each supergroup, until he began to experience the same difficulty as before. The second plateau in his performance curve (around block 21 in Fig. 1) is associated with difficulty in remembering the order of more than four groups within a supergroup. Introducing another level of organization by subdividing these supergroups allowed S.F.'s performance to improve rapidly so that he now averages almost 80 digits. His current retrieval organization can be described as a hierarchy with three levels, and his retrieval structure for 80 digits can be illustrated in the following way, with spaces corresponding to levels in the hierarchy:

444 444 333 333 444 333 444 5

Besides the verbal descriptions, there is a great deal of additional evidence that S.F. uses hierarchical retrieval structures. Probably the most straightforward evidence comes from his speech patterns during recall, which almost invariably follow the same pattern. Digit groups are recalled rapidly at a normal rate of speech (about 3 digits per second) with pauses between groups (about 2 seconds between groups, on average, with longer pauses when he has difficulty remembering). At the end of a supergroup, however, there is a falling intonation, generally followed by a longer pause *(5)*.

In several experiments, we verified that groups are retrieved through the hierarchical structure rather than through direct associations between groups. In one experiment, instead of asking for recall after presenting the digits, we presented S.F. with a 3- or 4-digit group and asked him to name the group that preceded it or followed it in the sequence. He required more than twice as long, on the average, if the preceding or following group crossed a supergroup boundary (10.0 seconds) than if it did not (4.4 seconds). In another experiment, after an hour's session, we presented S.F. with 3- and 4-digit groups from that session and asked him to recall as much as he could about each group. He invariably recalled the mnemonic associations he had generated, and he often recalled a great deal about the location of the group within the hierarchy, but he was virtually never able to recall the preceding or following group.

After all this practice, can we conclude that S.F. increased his short-term memory capacity? There are several reasons to think not. *(i)* The size of S.F.'s groups were almost always 3 and 4 digits, and he never generated a mnemonic association for more than 5 digits *(6)*. *(ii)* He almost never allowed his rehearsal group to exceed 6 digits. *(iii)* He generally used three groups in his supergroups, and, after some initial difficulty with five groups, never allowed more than four groups in a supergroup. *(iv)* In one experimental session, S.F. was switched from digits to letters of the alphabet after 3 months of practice and exhibited no transfer: His memory span dropped back to about six consonants.

These data suggest that the reliable working capacity of short-term memory is about three or four units, as Broadbent has recently argued *(7)*, and that it is not possible to increase the capacity of short-term memory with extended practice. Rather, increases in memory span are due to the use of mnemonic associations in long-term memory. With an appropriate mnemonic system and retrieval structure, there is seemingly no limit to improvement in memory skill with practice.

References and Notes

1. G.A. Miller, Psychol. Rev., 63, 81 (1956); A. Newell and H.A. Simon, Human Problem Solving (Prentice-Hall, Englewood Cliffs, N.J., 1972).

2. A.R. Luria has documented the case history of one exceptional person, S., who seemed to remember large amounts of trivial information for years by means of visual imagery [The Mind of a Mnemonist, (Avon, New York, 1968)], and E. Hunt and T. Love have described another exceptional person, V.P. who could remember large amounts of material by means of elaborate linguistic associations in several languages [in A.W. Mellon and E. Martin, Eds., Coding Processes in Human Memory(Winston, Washington D.C., 1972), p. 237].

3. S.F. is a good long-distance runner who competes in races throughout the eastern United States. He classifies running times into at least 11 major categories, from half-mile to marathon, with several subcategories within each.

4. The category label by itself was not sufficient to retrieve the exact digits presented. A complete understanding of the precision of mnemonic associations will require an answer to the more general question of how meaningful associations work.

5. Pauses, intonation, and stress patterns are well-known indicators of linguistic structures [M.A.K. Halliday, Intonation and Grammar in British English (Mouton, The Hague, 1967); K. Pike, The Intonation of American English (Univ. of Michigan Press, Ann Arbor, 1945)]. In one memory span study, we compared the grouping patterns indicated by the prosodic features in recall with the grouping patterns reported by S.F. in his verbal protocols, and agreement was virtually perfect.

6. The mnemonic associations of lighting calculators appear to be limited to 3 or 4 digits [G.E. Müller, A. Psychol. Ergänzungsbund. 5, (1911)].

7. D.A. Broadbent, in Studies in Long Term Memory, A. Kennedy and A. Wilkes, Eds., (Wiley, New York, 1975), p. 3].

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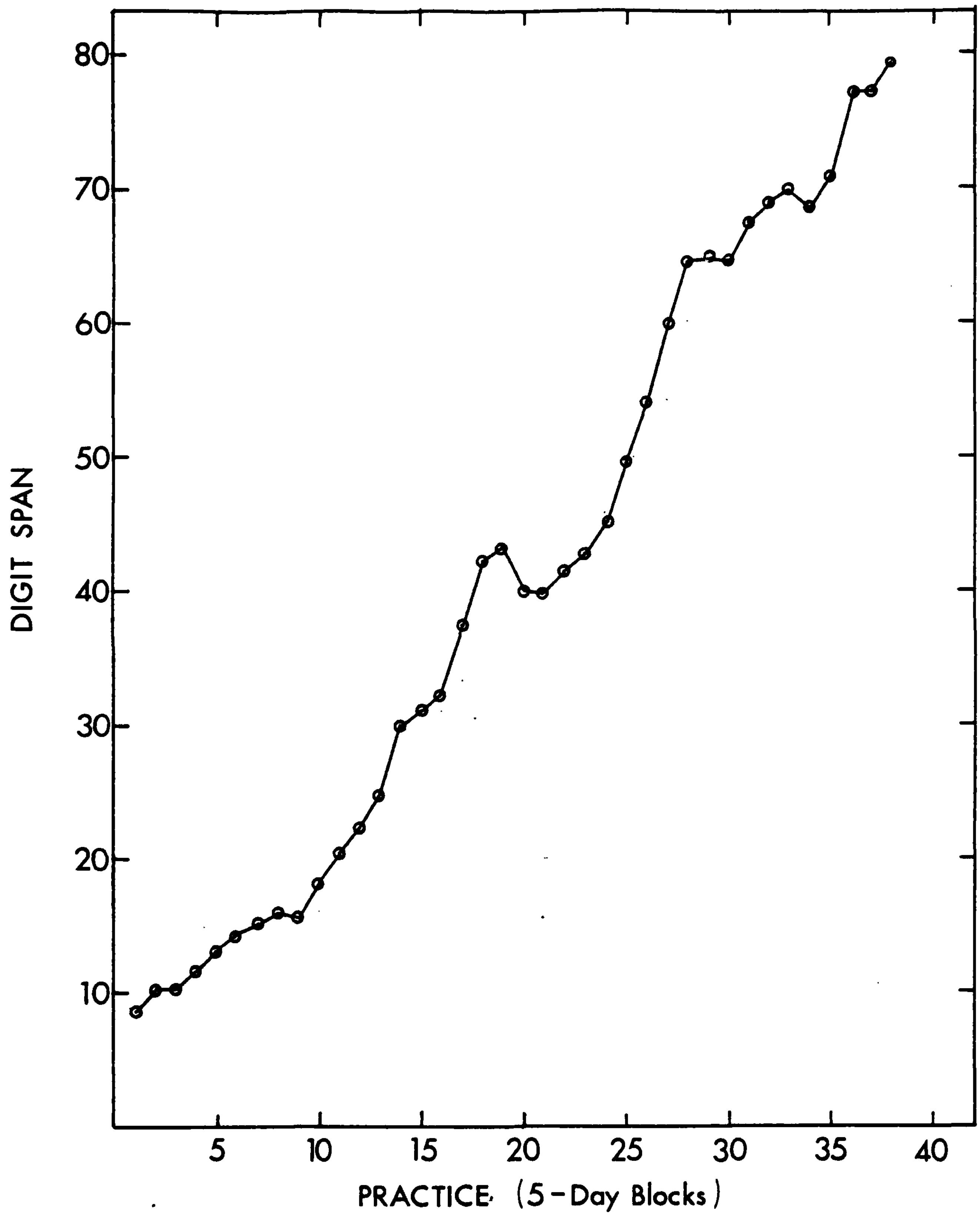
Figure 1.

Average digit span for S.F. as a function of practice. Digit span is defined as the length of the sequence that is correct 50 percent of the time; under the procedure followed, it is equivalent to average sequence length. Each day represents about 1 hour's practice and ranges from 55 trials per day in the beginning to 3 trials per day for the longest sequences. The 38 blocks of practice shown here represent about 190 hours of practice; interspersed among these practice sessions are approximately 40 hours of experimental sessions (not shown).



DIGIT SPAN
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PRACTICE (5-Day Blocks)

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